Dynamics Fracture Propagation due to Cold Water Injection

by

Muhammad Abduh Bin Mustapha

Dissertation submitted in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)

(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD ABDUH BIN MUSTAPHA

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Abstract:

Hydraulic fracturing is a well stimulation technique to improve hydrocarbon recovery. Despite the research done in the past several decades, numerical simulation of dynamic fracture propagation remains a challenging topic in the oil and gas industry.

This project investigated the fracture propagation in a cold water injection scenario based on several models in hydraulic fracturing. Moreover, this project intends to quantify the stability of fracture and the leak-off rate at the fracture surfaces. Other than that, computational tool is developed to simulate the fracture propagation and project in a Graphical User Interface.

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CHAPTER 1: INTRODUCTION

The hydraulic fracturing technique of well stimulation is one of the major developments in petroleum engineering since the last fifty (50) years. The technique was introduced to the petroleum industry in a paper by J.B Clark, of the Stanolind Oil and Gas Co. in 1948 and since then its use has progressively expanded so that by the end of 1955 more than 100,000 individual treatments had been performed.

This technique is mechanically related to three other phenomena concerning which an extensive literature developed by J. B. Clark (1948). Those three are phenomena pressure parting in water injection wells in secondary-recovery operations, lost circulation during drilling, and the breakdown of formation during squeeze-cementing operations. First in pressure parting in water injection wells in secondary-recovery operations the water is being pumped through the injection well into the reservoir displaces the oil and drives the oil towards the production well.

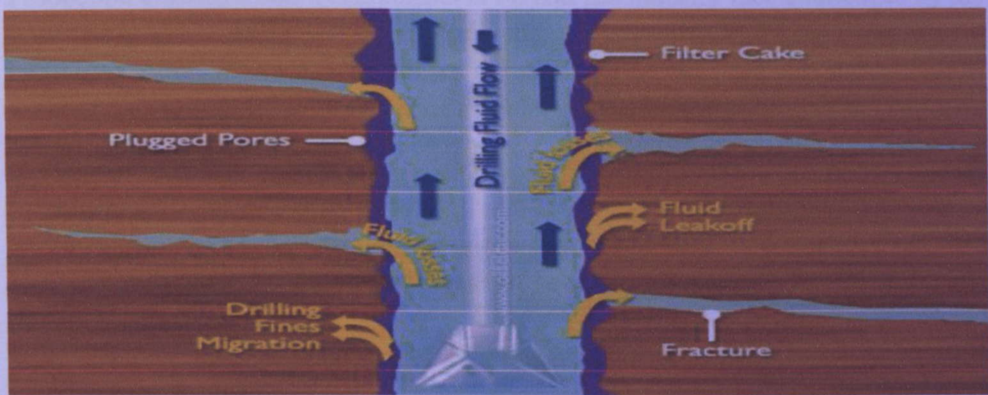

Figure 1.1 shows the lost circulation during drilling – fluids or mud disappear into the formation.

Secondly, problem lost circulation during drilling shown in Figure 1 above is regarding the mud used to drill the well may suddenly disappear into a formation previously penetrated by the bit. It may be caused by excessive mud weight which may rupture the formation while the mud disappears into the newly formed fractures. Last but not the least is the breakdown of formation during squeeze-cementing operations. It may be visualised that the cement moved in as a horizontal pancake thus reducing the vertical movement of fluids and then shutting of the flow of the water.

Thus, relation of those three problems is related in hydraulic fracturing as the application of fluid pressure to a desired section of a formation until rupture occurs. Continual pumping extends the break, thus creating a new and larger flow channel to the well bore. In this topic, Dynamics Fracture Propagation due to Cold Water Injection, problems identified based on statement of van Poolen (1948) are fracture initiation and its propagation due to cold water injection and the instability of the fracture and increasing in leak-off rate at its surface.

Van Poolen (1957) stated rock mechanics has been given definite consideration in the petroleum industry. The problems of rock mechanics start the moment a rock bit penetrates the top soil and these problems will exist until the well has been abandoned. The complexity of the problems is of such an order that rules of thumb are usually followed, supported by day-to-day experience to overcome the difficulties encountered.

Hagoort (1980) had come out a model which is capable in simulating fracture propagation as a function of injection and production rates or pressures, reservoir fluid properties, and formation-fracturing pressures.

Problem Statement

Production engineers and technologists in oil and gas industry face challenges by the uncertainty of wellbore stability especially in latest treatment hydraulic fracturing. Until now geologist and petrophysicists are still figuring out what is really going in the Earth along with other phenomena associated with it. The questions can be simply put as per below:

1. What does the wellbore looks alike?
2. How does fracture propagation occurs by a cold water injection?
3. What are the relevant equations must be taken account to investigate this fracture propagation?
4. What are the assumptions for simplifications in the concept of fracture propagation?
5. What are the parameters related to this fracture propagation?
6. When will it be the fracture stop to propagate?

Many studies have been done in hydraulic fracturing and rock mechanics associated with it but still nobody can explain the exact pictures inside the Earth especially the wellbore formation. Thus, this project intends to calculate fracture length and fracture propagation approximately while trying the best way to illustrate hydraulic fracturing treatment.

Objective of Study

There are three identified objectives to be achieved from this topic:

i. Investigate the fracture initiation along with its propagation in a cold water injection scenario,

ii. Quantify the stability of fracture and leak-off rate at the fracture surface, and

iii. Develop an in-house software which can stimulate a well simulate reservoir.

CHAPTER 2: LITERATURE REVIEW

2.1 Origin of Hydraulic Fracturing

Before 1950s explosives, acidizing, and other methods have long been used to improve productivity oil and gas wells particularly for wells which produce from formations which do not react readily with acids. Hydraulic Fracturing, "Hydrafac", shows distinct promise of increasing production rates from wells producing from any type of formation. The method is also considered applicable to gas and water injection wells, wells used for solution mining of salts and with some modification to water wells and sulphur wells.

A possible process with certain requirements had been met by J. B. Clark (1949) as follows:

i. The hydraulic fluid selected must be sufficiently viscous that it can be injected into the well at pressure high enough to cause fracturing.
ii. The hydraulic fluid should carry in suspension a propping agent, such as sand, so that once a fracture is formed it will be prevented from closing off and the fracture created will remain to serve as a flow channel for oil and gas.
iii. After the fracture is made it is essential that the fracturing fluid be thin enough to flow back out of the well and not stay in place and plug the crack which it has formed.
iv. In many instances, formation packers must be used to confine the fracture to the desired level and to obtain the advantages of multiple fracturing.

2.2 State of Stress Underground

The general stress condition underground is therefore one in which the three mutually perpendicular principal stresses are unequal. If fluid pressure were applied locally within rocks in this condition and the pressure increased until rupture or parting of the rocks results, that plane along which fracture or parting is first possible is the one perpendicular to the least principal stress. Figure 2.1 shows stress element and preferred plane of the fracture.

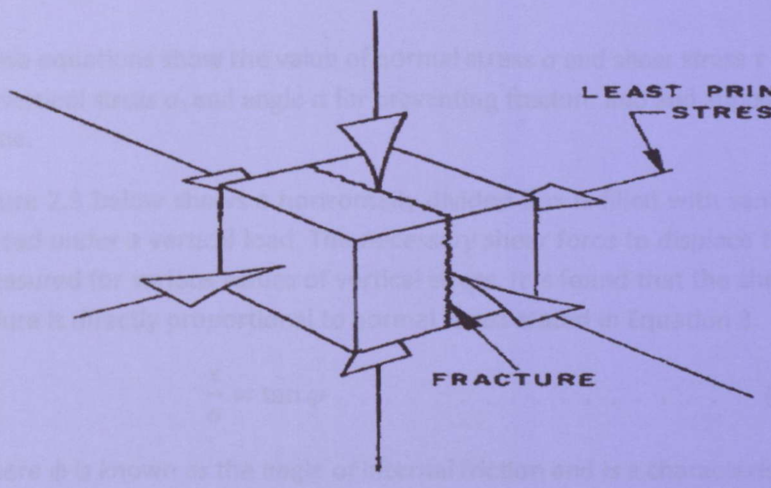

Figure 2.1: Stress element and preferred plane of fracture.

Balanced equilibrium forces between normal stress σ and shear stress τ acting across a plane perpendicular to the σ_1, σ_3-plane and making an arbitrary angle α with the direction of least principal stress σ_3 is shown in Figure 2.2.

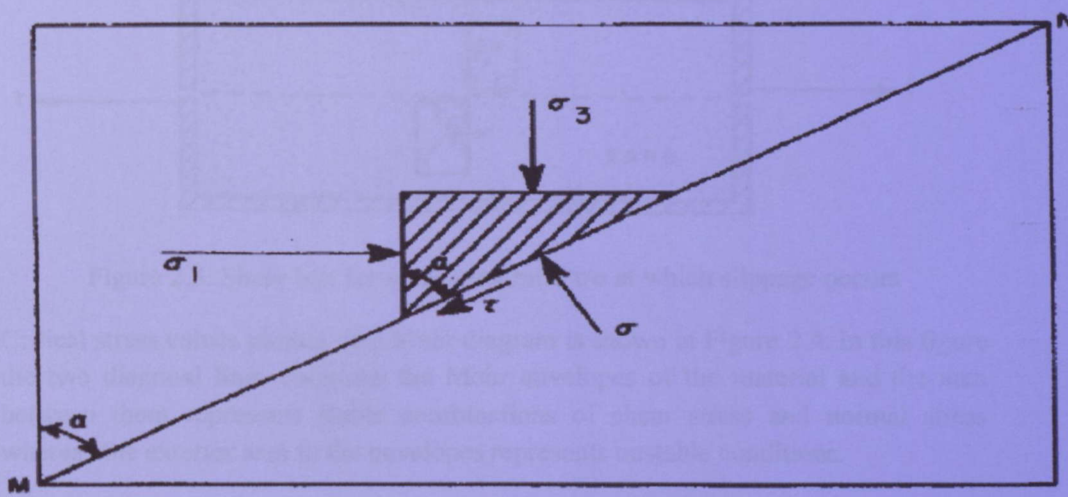

Figure 2.2: Stresses σ and τ on plane of arbitrary angle α

Mohr stress presentation consists in plotting values of normal and shear stress from Equation 1 and 2 below with respect to σ and τ-coordinate axes for all possible values of the angle α as shown in Figure 2.2.

$$\sigma = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2}\cos 2\alpha . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\tau = \frac{\sigma_1 - \sigma_3}{2}\sin 2\alpha . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where σ_1 is vertical stress and σ_2 is the horizontal stress acted upon the plane.

These equations show the value of normal stress σ and shear stress τ depend mainly on vertical stress σ_1 and angle α for preventing fracture into and slippage onto the plane.

Figure 2.3 below shows a horizontally divided box is filled with sand which is then placed under a vertical load. The necessary shear force to displace the upper box is measured for various values of vertical stress. It is found that the shearing stress for failure is directly proportional to normal stress stated in Equation 3.

$$\frac{\tau}{\sigma} = \tan \varphi \; . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where ϕ is known as the angle of internal friction and is a characteristic of the material.

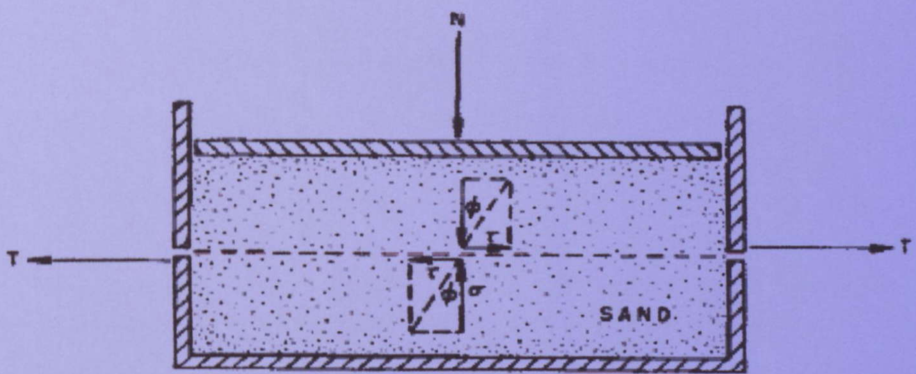

Figure 2.3: Shear box for measuring ratio τ/σ at which slippage occurs

Critical stress values plotted on a Mohr diagram is shown in Figure 2.4. In this figure the two diagonal lines comprise the Mohr envelopes of the material and the area between them represents stable combinations of shear stress and normal stress whereas the exterior area to the envelopes represents unstable conditions.

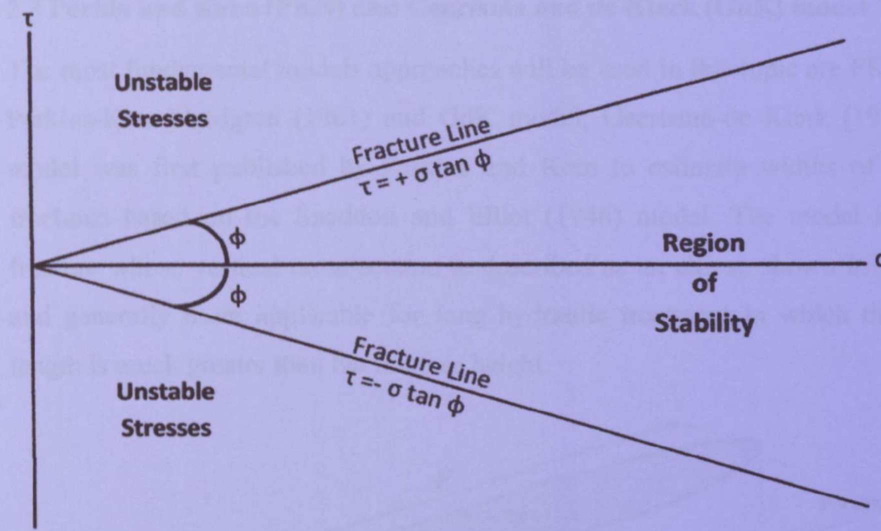

Figure 2.4: Mohr envelops for sand showing curves of values of σ and τ at which slippage occurs

From this figure it shows that stress stability depends on the angle of internal friction ϕ and amount of normal stress. Higher stress applied to the plane requires higher amount of shear strain for the plain to fracture.

2.3 Perkin and Kern (PKN) and Geertsma and de Klerk (GdK) model

The most fundamental models approaches will be used in this topic are PKN model; Perkins-Kern-Nordgren (1961) and GdK model; Geertsma-de Klerk (1972). PKN model was first published by Perkins and Kern to estimate widths of hydraulic fractures based on the Sneddon and Elliot (1946) model. The model involves a fracture whose vertical cross-section is described as an ellipse shown in Figure 2.5 and generally more applicable for long hydraulic treatment in which the fracture length is much greater than the fracture height.

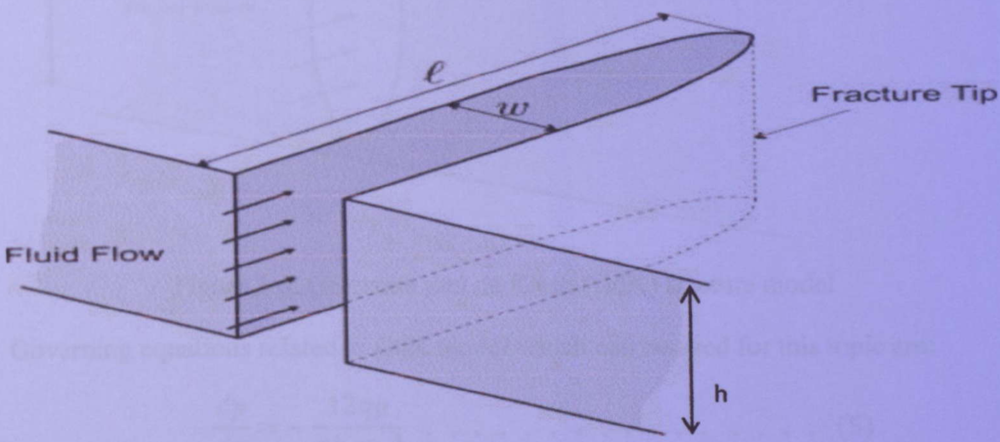

Figure 2.5: Perkins and Kern (PKN) fracture model

Governing equations related to PKN model which can be used for this topic are:

$$\frac{dp}{dx} = -\frac{64q\mu}{\pi h_f {w_f}^3} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where p is pressure, x is the distance along the fracture, μ is fluid viscosity, and h_f is height of the fracture, q is fluid flow rate, and w_f is the fracture width.

$$p_{net} = \left[\frac{16\mu q_i E'^3}{\pi {h_f}^4} L\right]^{1/4} \quad \ldots\ldots\ldots\ldots \quad (4)$$

where q_i is the initial injection flow rate, E' is the Young' s Modulus.

Width at the wellbore (x = 0) can be found by using Equation 5:

$$w_w = 0.38\left(\frac{q_i \mu L}{E'}\right)^{1/4} \quad \ldots\ldots\ldots\ldots \quad (5)$$

GdK model (1972) shown in Figure 2.6 involves a fracture whose horizontal cross-section can be described by an ellipse and more applicable towards short hydraulic treatments in which the vertical extent is relative larger than to the horizontal extent.

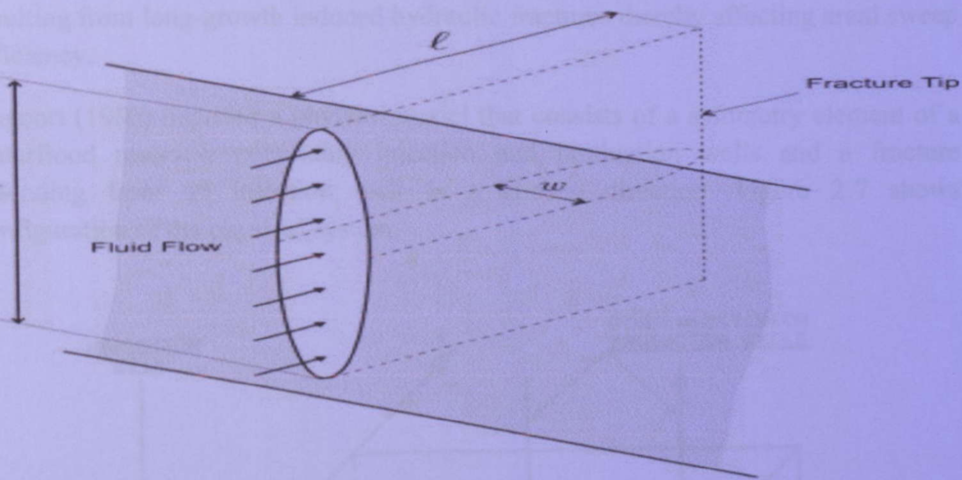

Figure 2.6: Geertsma and de Klerk (GdK) fracture model

Governing equations related to GdK model which can be used for this topic are:

$$\frac{dp}{dx} = -\frac{12q\mu}{\pi h_f w_f{}^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

where p is pressure, x is the distance along the fracture, μ is fluid viscosity, and h_f is height of the fracture, q is fluid flow rate, and w_f is the fracture width.

$$p_{net} \approx \left[\frac{21\mu q_i E'^3}{64\pi h_f{}^2} L\right]^{\frac{1}{4}} \quad \ldots\ldots\ldots\ldots\ldots \text{(6)}$$

where q_i is the initial injection flow rate and E' is the Young^' s Modulus.

Width at the wellbore (x = 0) can be found by using Equation 5:

$$w_w = \left(\frac{84 q_i \mu L}{\pi E' h_f}\right)^{1/4} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

2.4 Physical Model of Hagoort

Formation-fracturing pressures often exceeded injection pressures in water-injection wells either unintentionally or by design. Even though from its bright side can leads to improved injectivity however it jeopardize the flooding efficiency of waterfloods resulting from long-growth induced hydraulic fractures thereby affecting areal sweep efficiency.

Hagoort (1980) depicted a physical model that consists of a symmetry element of a waterflood reservoir containing injection and production wells and a fracture extending from an injection well in a chosen direction. Figure 2.7 shows configuration of the physical system.

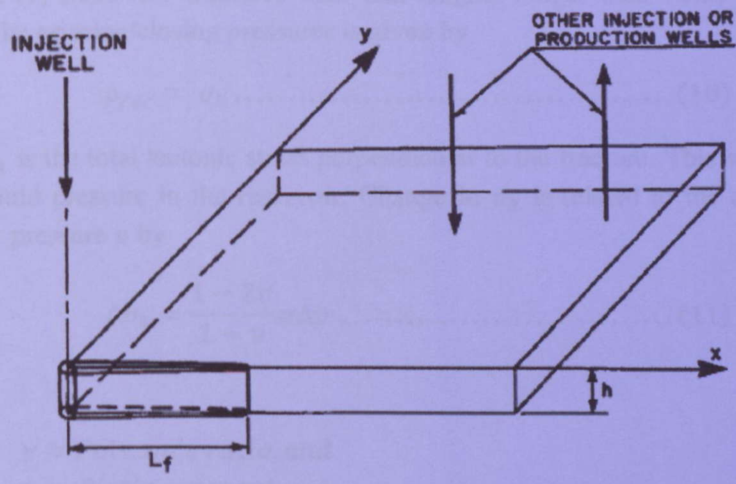

Figure 2.7: Configuration of physical system by Hagoort (1980)

This physical model has a uniform or slightly varying thickness that is small relative to the areal dimensions in the reservoir. Mobility ratio of the water-flood is M=1.0. Fluid flow in the reservoir of this system can be approximated by the equation for two-dimensional single phase compressible flow.

$$\frac{\partial}{\partial x}\left[\frac{k_x}{\mu B}\left(\frac{\partial p}{\partial x}-\rho g\frac{\partial z}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[\frac{k_y}{\mu B}\left(\frac{\partial p}{\partial y}-\rho g\frac{\partial z}{\partial y}\right)\right]=K_c\frac{\partial p}{\partial t}+Q\,\dots\dots\,(8)$$

where p is fluid pressure, k is permeability, μ is viscosity, ρ is density, B is formation volume factor, z is depth, K_c is compressibility coefficient, and Q is source or sink.

During fracture propagation the pressure in the fracture equals the propagation pressure which is given by Hagoort (1980) as:

$$p_{fp} = p_{foc} + \frac{K_{IC}}{\sqrt{\pi L_f}} \text{..............................} (9)$$

where;

$p_{fp} = propagation\ pressure$
$p_{foc} = fractureopening/closingpressure$
$K_{IC} = cricitcal\ stress - intensity\ factor, and$
$L_f = fracture\ half - length$

Equation (9) holds for fractures with half-lengths longer than twice the wellbore radius. The opening/closing pressures is given by

$$p_{foc} = \sigma_h \text{..} (10)$$

where σ_h is the total tectonic stress perpendicular to the fracture. This stress depends on the fluid pressure in the reservoir. Change in σ_h is related to the change in the reservoir pressure p by

$$\Delta\sigma_h = \frac{1-2v}{1-v}\alpha\Delta p \text{ ....} (11)$$

where;

$v = Poisson's\ ratio, and$
$\alpha = Biot's\ constant$

In the physical model Δp is interpreted as the change in average pressure p_{avg} of the symmetry element of the waterflood pattern. Futhermore, fracture initiation occurs if the pressure in the wellbore reaches a value corresponding to the propagation pressure of a fracture with half-length L_f; the initial value with which the fracture begins to propagates.

$$p_{fi} = p_{foc} + \frac{K_{IC}}{\sqrt{\pi L_{fi}}} \text{..............................} (12)$$

The initial fracture half-length L_{fi} in Equation 12 should be at least twice the wellbore radius, the smallest fracture half-length L_f which Equation 9 still holds.

An open linear fracture at a uniform pressure p_f takes an elliptic shape in the areal plane L_f as the semimajor axis and semiminor axis (the fracture half-width) given by

$$w_f = \frac{2(1-v^2)L_f}{E}(p_f - p_{foc}) \text{....................} (13)$$

where E is Young's Modulus.

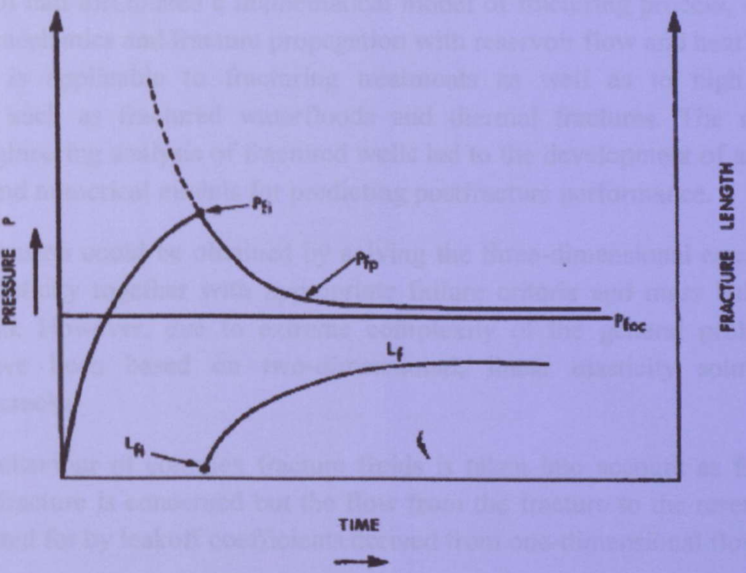

Figure 2.8: Fracture pressure and fracture length as a function of time

The fracture growth is based on Carter's fracture propagation model. According to Carter (1957), hydraulic fractures can propagate only if there is fluid available to fill up the fracture. Hence, fracture propagation follows a mass-material balance of the fracture. This balance is written as:

$$\frac{d(\frac{V_{fracture}}{B})}{dt} = i_i - q_{loss} \text{. . . . .} \quad (14)$$

where $V_{fracture}$ is the fracture quarter-volume and B is formation volume factor.

If losses exceed injection an open fracture does not recede but starts closing. Currently the fracture-closing mechanism in the model may close completely. The fractures stay propped open by loose rock particles eroded from the fracture face. This may indicate the fracture stability however further study is needed resolve this problem of fracture closure.

2.5 Simulation of Hydraulic Fracturing Processes

Settari (1980) had formulated a mathematical model of fracturing process, coupling the fracture mechanics and fracture propagation with reservoir flow and heat transfer. The model is applicable to fracturing treatments as well as to high leakoff applications such as fractured waterfloods and thermal fractures. The need for reservoir engineering analysis of fractured wells led to the development of analytical techniques and numerical models for predicting postfracture performance.

Fracture extension could be obtained by solving the three-dimensional equations of nonlinear elasticity together with appropriate failure criteria and mass balance on injected fluid. However, due to extreme complexity of the general problem the analyses have been based on two-dimensional, linear elasticity solutions of equilibrium cracks.

Nonlinear behaviour of complex fracture fluids is taken into account as far as the flow in the fracture is concerned but the flow from the fracture to the reservoir has been accounted for by leakoff coefficients derived from one-dimensional flow.

Heat transfer is important when the fluid properties are sensitive to temperature. Heat transfer is linked intimately to fluid flow in particular to the leakoff distribution along the fracture face and it also can affect the stress field significantly.

Hagoort (1978) had derived equations for fracture initiation pressure p_{fi}, fracture propagation pressure p_{fp}, and fracture opening or closing pressure p_{foc} which consider the effect of pore pressure. The resulting equations used in simulator are:

$$p_{fi} = \frac{2\left(\frac{v}{1-v}\right)\sigma_v + 2\sigma_{Hi} + A_{pe}p + \sigma_t}{2 - A_{pe}} \quad \ldots\ldots\ldots\ldots \quad (8)$$

$$p_{fi} = p_{foc} + \frac{\sigma_t/2}{1 - A_{pe}/2} \quad \ldots\ldots\ldots\ldots \quad (9)$$

where A_{pe} is the poroelastic constant, σ_v is the vertical stress, σ_{Hi} is the initial horizontal stress, and v is the Poison's ratio.

$$p_{foc} = \frac{\left(\frac{v}{1-v}\right)\sigma_v + \sigma_{Hi} + A_{pe}p/2}{1 - A_{pe}/2} \quad \ldots\ldots\ldots\ldots \quad (10)$$

$$= \frac{\sigma_H - A_{pe}p/2}{1 - A_{pe}/2} \quad \ldots\ldots\ldots\ldots \quad (11)$$

where σ_H is the horizontal stress.

$$p_{fp} = p_{foc} + \frac{\left[\frac{2E\gamma}{L_f(1-v^2)}\right]^{1/2}}{1 - A_{pe}/2} \quad \ldots\ldots\ldots\ldots \quad (12)$$

CHAPTER 3: METHODOLOGY

3.1 Research Methodology

Interpretation obtained from the literature adduces fracture propagation take account from both fracture pressure and fracture length simultaneously. Generally five steps are required to perform the fracture simulation in the methodology shown in Figure 3.1.

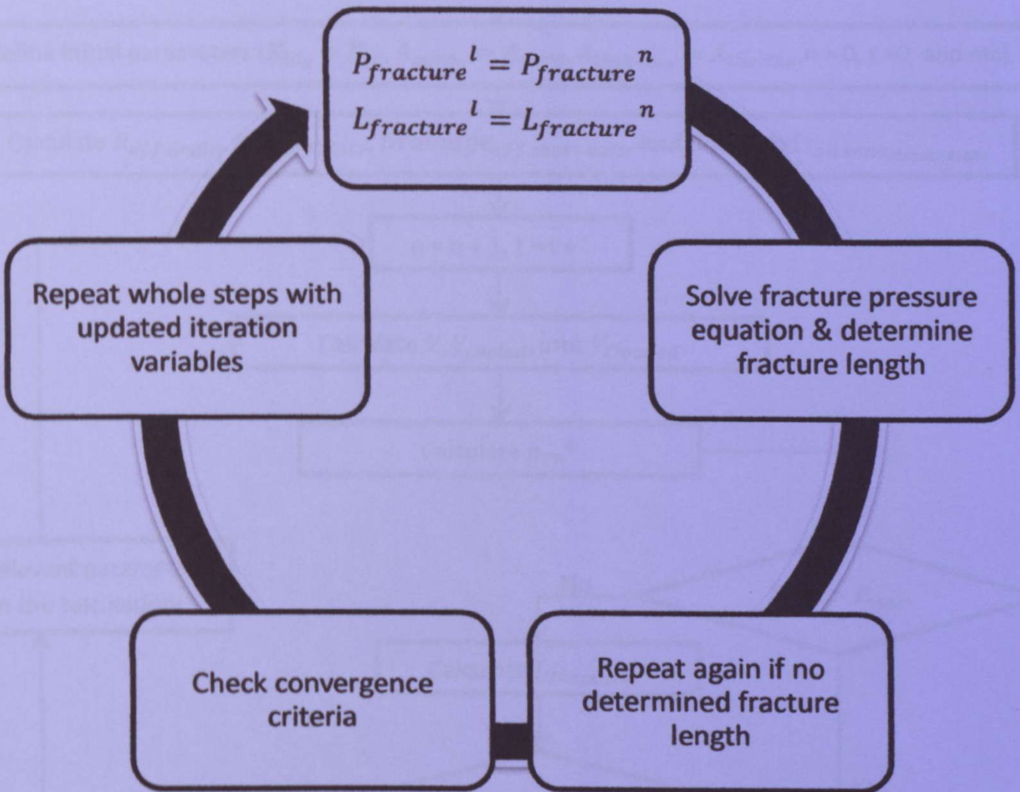

Figure 3.1: Research methodology of this topic

Fracture pressure and fracture length equations must be solved first furthermore must meet the convergence criteria to avoid any irrelevant value. Iteration variables or parameters are updated and the process is repeated from the beginning until latest injection time is reached.

3.2 FracAnalyse Simulation

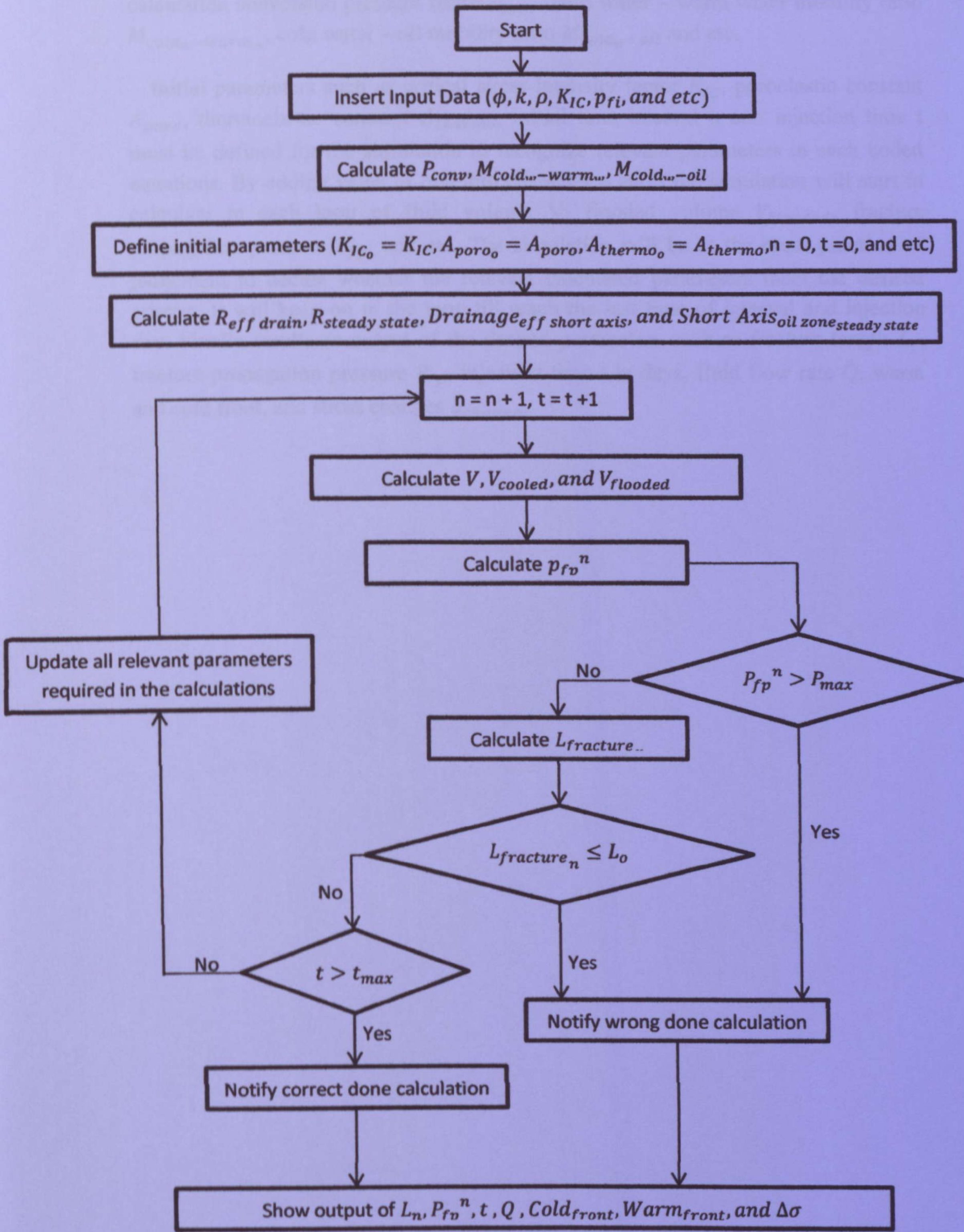

Figure 3.2: Schematic flow chart of FracAnalyse simulation

The simulation in Figure 3.2 starts by key-in relevant input data and following by calculation conversion pressure factor P_{conv}, cold water – warm water mobility ratio $M_{cold_w-warm_w}$, cold water – oil mobility ratio M_{cold_w-oil} and etc.

Initial parameters such as critical stress-intensity factor K_{IC}, poroelastic constant A_{poro}, thermoelastic constant A_{thermo}, initial time interval n and injection time t must be defined for the simulation to recognize relevant parameters in each coded equations. By adding value of one into character n and t the simulation will start to calculate in each loop of fluid volume V, flooded volume $V_{flooded}$, fracture propagation pressure P_{fp}, and etc. The simulation will be at the cross junction of judgement to decide whether the relevant calculated parameters meet the desired criteria. It will keep on in the loop till reach the last time of interval and injection day. Finally results or output of the desired parameters such as fracture length L_f, fracture propagation pressure P_{fp}, injection time t in days, fluid flow rate Q, warm and cold front, and stress changes σ_{change}.

3.2 Project Activities, Key Milestones and Gantt Chart

Project Activities	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Phase 1: Preliminary Research Work								Mid-semester break							
PKN and GdK model															
Fracture Initiation and Propagation															
Cold Water Injection Effect															
Well simulation loop operation															

Table 3.1: 1st Phase Project Activities (Preliminary Research Work)

Project Activities	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Phase 2: Research on well simulator software								Mid-semester break							
Source code for the well simulation software															
Related parameters, variable, and constants															
Select significant equations to be used															

Table 3.2: 2nd Phase Project Activities (Research on well simulator software)

Project Activities	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Phase 3: Try-and-error on small scale well simulation								Mid-semester break							
Develop a small well simulation in a small-scale reservoir															
Identify and debug erroneous source code															
Run through again the simulation															

Table 3.3: 3rd Phase Project Activities (Try-and-error on small scale well simulation)

Project Activities	11	12	13	14		15	16	17	18	19	20	21		22	23	24	25	26	27	28
Phase 4: Simulate a large-scale reservoir well					Semester break								Mid-semester break							
Achieve three (3) relative-same results																				
Identify end results of fracture length, fracture stability, and leak-off rates																				

Table 3.4: 4th Phase Project Activities (Simulate a large-scale reservoir well)

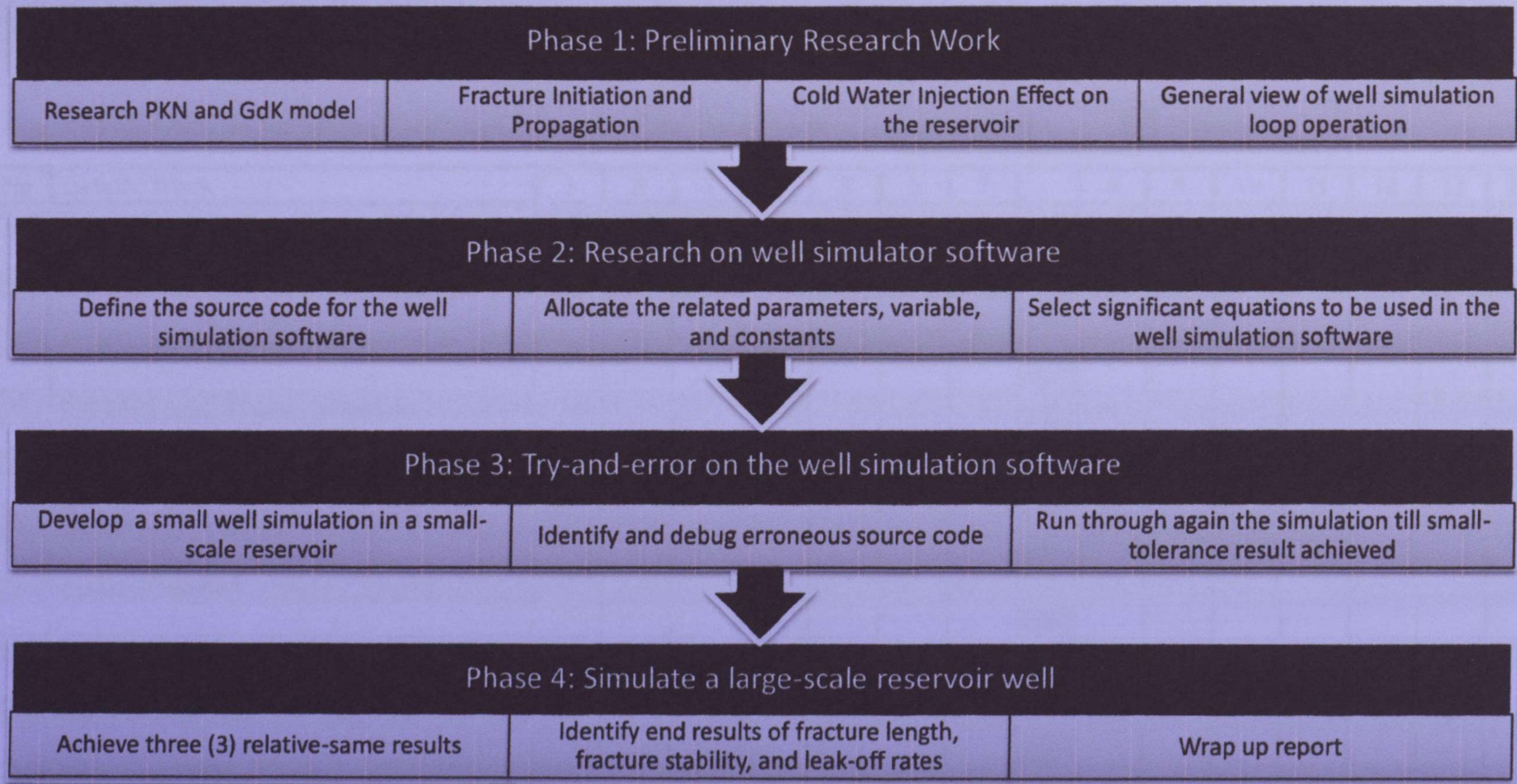

Figure 3.3: General view workflow phases of all project activities

Suggested Milestone for the Second Semester of 2-Semester Final Year Project

• Milestone ■ Process

No	Detail / Work	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work continue	■	■	■					Mid – semester break							
2	Submission of Progress Report 1				•											
3	Project Work continue				■	■	■	■								
4	Submission of Progress Report 2									•						
5	Seminar										■	■	■			
6	Project Work continue									■	■	■	■			
7	Poster Exhibition											•				
8	Submission of Dissertation (soft bound)													•		
9	Oral Presentation														•	
10	Submission of Project Dissertation (hard bound)															•

Table 3.6: Milestones and Gantt Chart for second (2^{nd}) semester FYP

CHAPTER 4 : RESULTS AND DISCUSSIONS

Three(3) main results had been obtained in this topic cover spreadsheets, graphic results, and FracAnalyse,.

4.1 Spreadsheets

Example generated worksheets from this Excel VBA are shown as per above:

Formation Data	Value
Injection Rate – Q (m^3/day)	1000
Injection Volume – V (m^3)	200000
Initial Fracture Length – Li (m)	0.1
Time of First Length Calculation – To (days)	1
Time of Last Length Calculation – T1 (days)	365

Reservoir Rock Properties	Value
Permeability – k (darcy)	0.25
Porosity – ϕ (fraction)	0.3
Heat Capacity of Base Rock – HCCR (kJ/m^3.°C)	2100
Thermal Conductivity of Base Rock – LAMB (W/m.°C)	2.5
Reservoir Rock Thermoelastic Constant – A_{thermo} (bar/°C)	0.6
Reservoir Rock Poroelastic Constant – A_{poro} (bar/°C)	1
Fracture Toughness - K_{ic} (bar.√m)	10

Supply Fluid Properties	Value
Cold Water Viscosity – μ_{cold} (cP)	1
Warm Water Viscosity – μ_{warm} (cP)	0.5
Oil viscosity - μ_{oil} (cP)	110
Total compressibility – c (1/bar)	0.015
Volume fraction of Oil/Sands in Fluid – FRACEX (fraction)	0.1
External Permeability Damage Factor – DAMEX (fraction)	0.00004
Volume fraction of Oil/Sands in Fluid – FRACIN (fraction)	0.3
Internal Permeability damage factor – DAMINT (fraction)	0.1

Table 4.1 : Spreadsheet of FracAnalyse simulator parameters

Parameters within the spreadsheet are partial from the exact spreadsheet in the software simulation. Crucial parameters change the whole graph results are the last four which are Volume fraction of Oil/Sand in Fluid FRACEX, External permeability Damage Factor DAMEX, Volume fraction of Oil/Sands in Fluid FRACIN, and Internal permeability damage factor DAMINT. Pressure rise in fracture is affected by these parameters along with semi axes of internal filtercake zone which is calculated based on initial pressure $P_{initial}$, flooded volume $V_{flooded}$, fracture length L_f, and reservoir height H.

4.2 Graphical Results

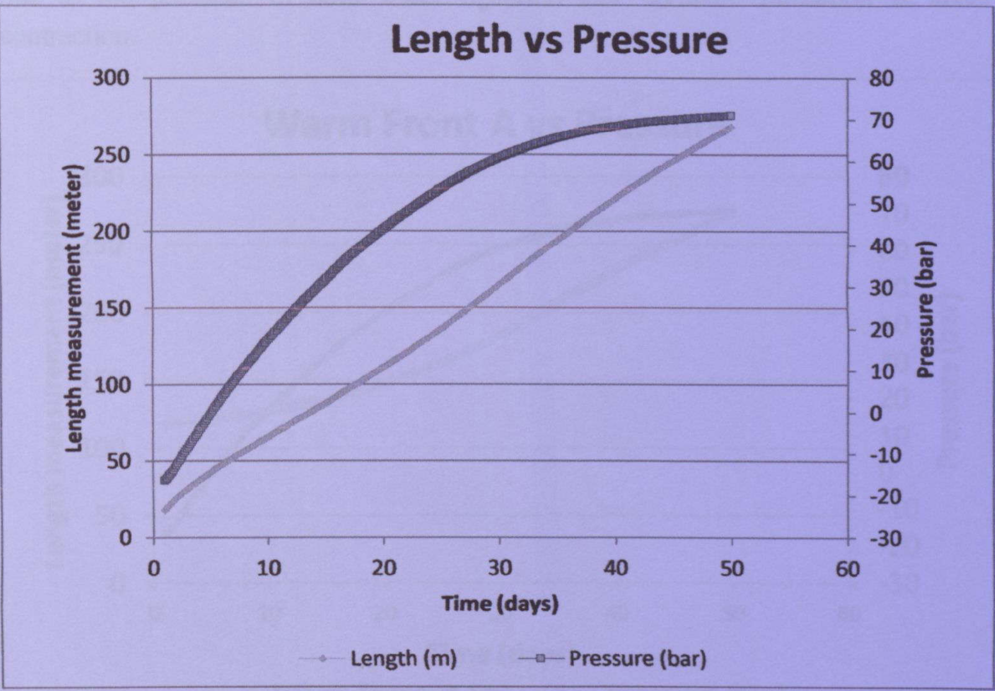

Figure 4.1: Result Fractured Length versus Pressure

Information extracted from the generated result in Figure 4.1 indicates as the fractured length L_f increases the required pressure P must be applied must be increased to prevent any loss circulation in the borehole.

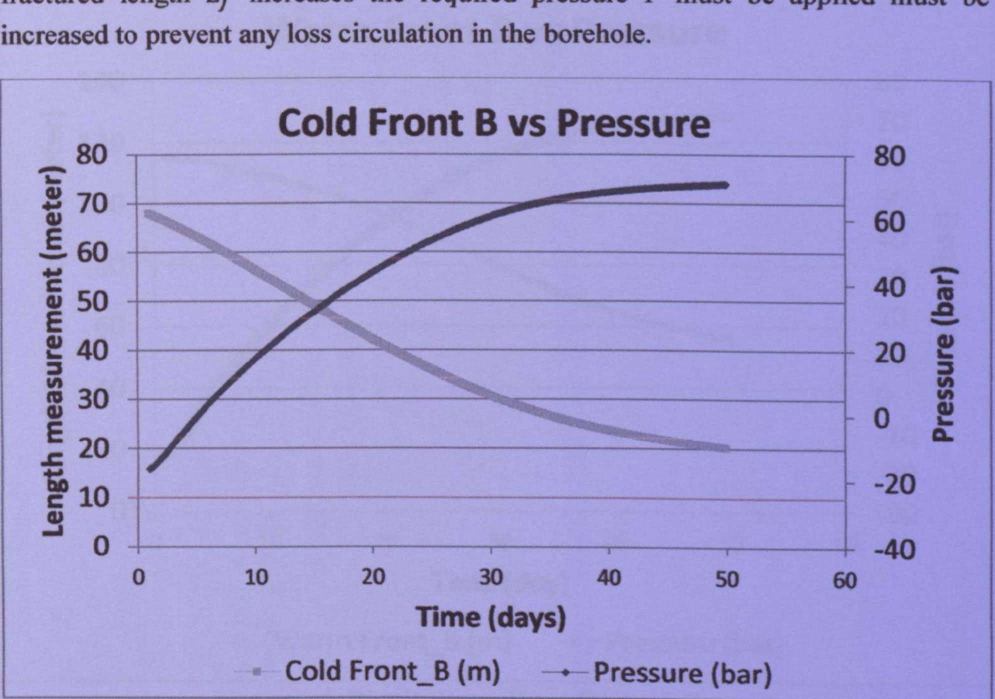

Figure 4.2: Result Cold Front Area versus Pressure

Looking from the Figure 4.2 clearly cold front area shrinks as the pressure increases due to the presence of cold water injection and borehole formation is under contraction.

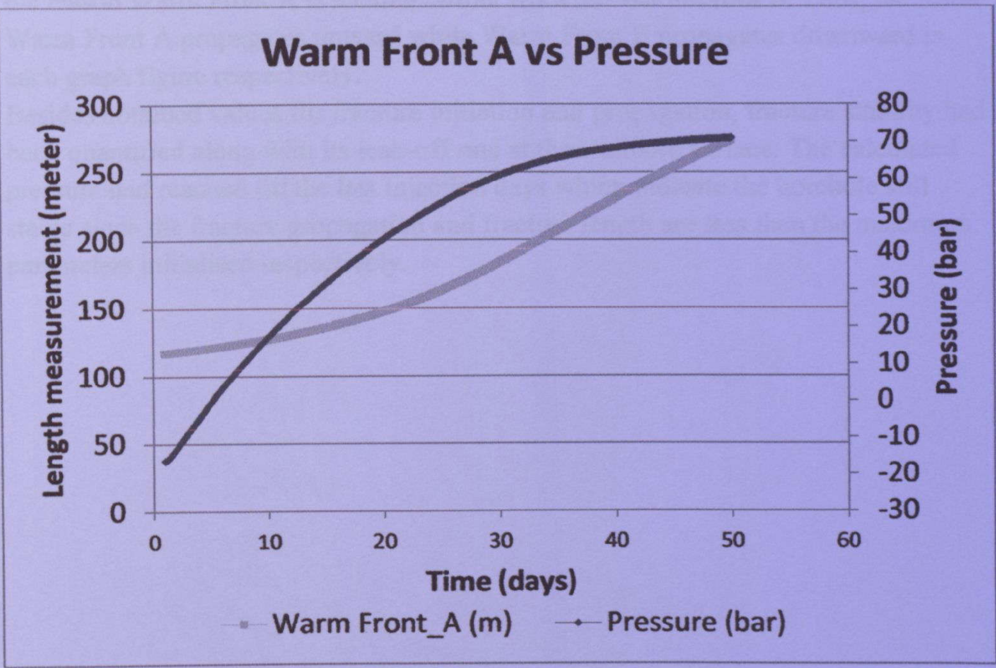

Figure 4.3: Result Warm Front A versus Pressure

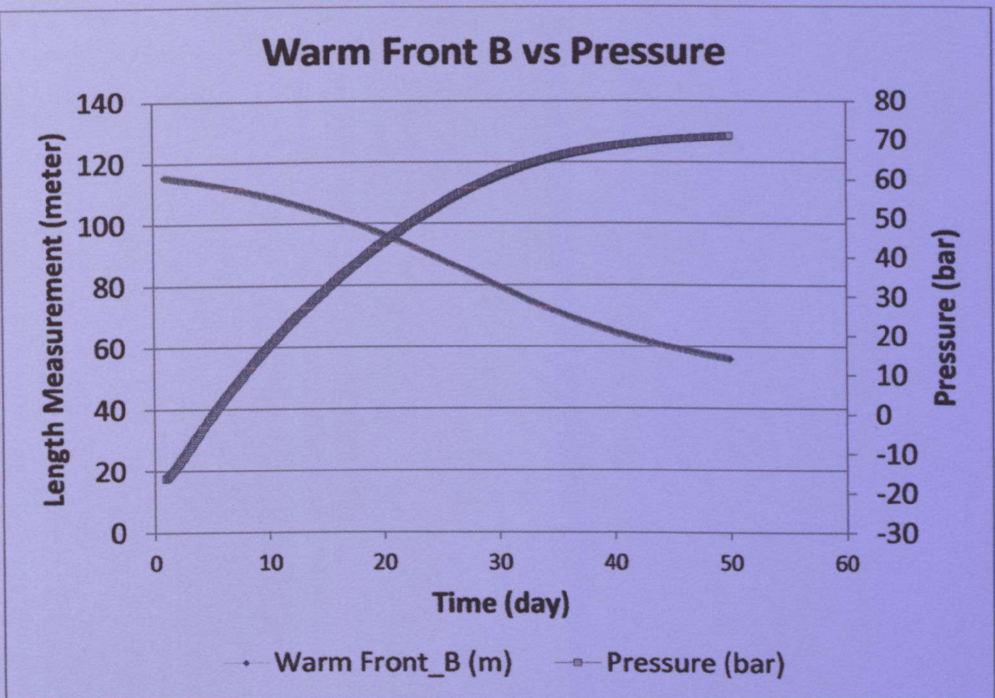

Figure 4.4: Result Warm Front B versus Pressure

Unmatched results in both Figure 4.3 and 4.4 under the same category of warm front are due to their location situated in different region. Warm Front A in Figure 4.3 increases while Warm Front B in Figure 4.4 is behaving at opposing side because of the reason Warm Front A is located farther from the Warm Front B. Thus, the result Warm Front A propagates upward while Warm Front B propagates downward in each graph figure respectively.

Besides obtained values for fracture initiation and propagation, fracture stability had been quantified along with its leak-off rate at the wellbore surface. The calculated pressure had reached till the last injection days which indicate the borehole still stable since the fracture propagation and fracture length are less than the maximum parameters initialised respectively.

4.3 FracAnalyse

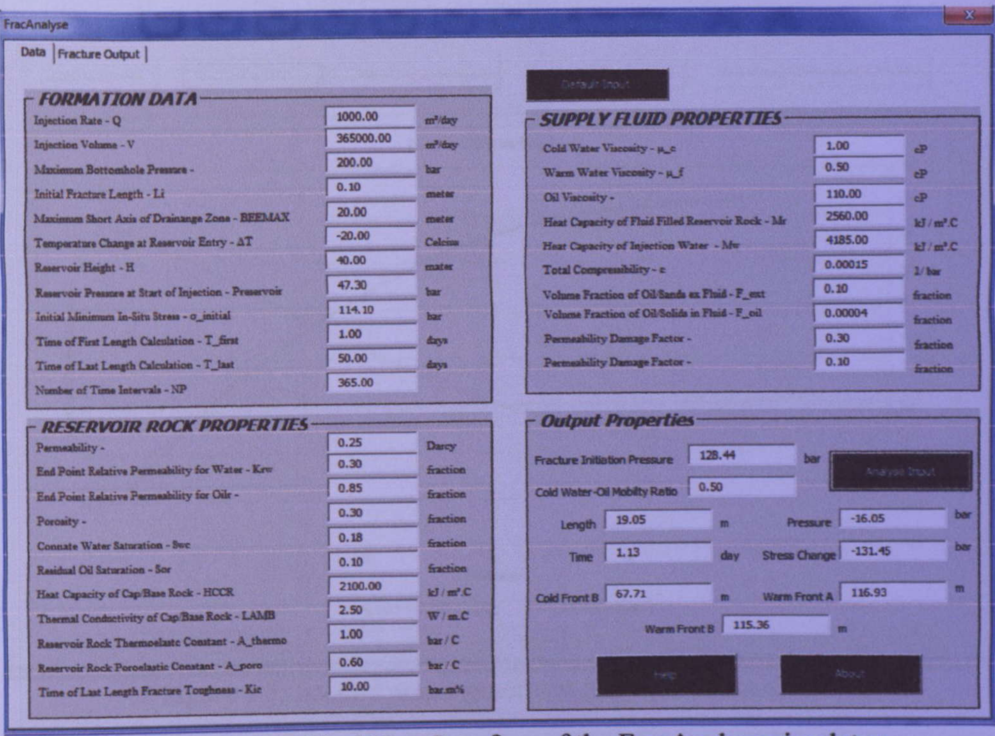

Figure 4.5: Graphical User Interface of the FracAnalyse simulator

Other than inserting the input data into the FracAnalyse as shown in Figure 4.5 output parameters or properties will be shown automatically on the interface.

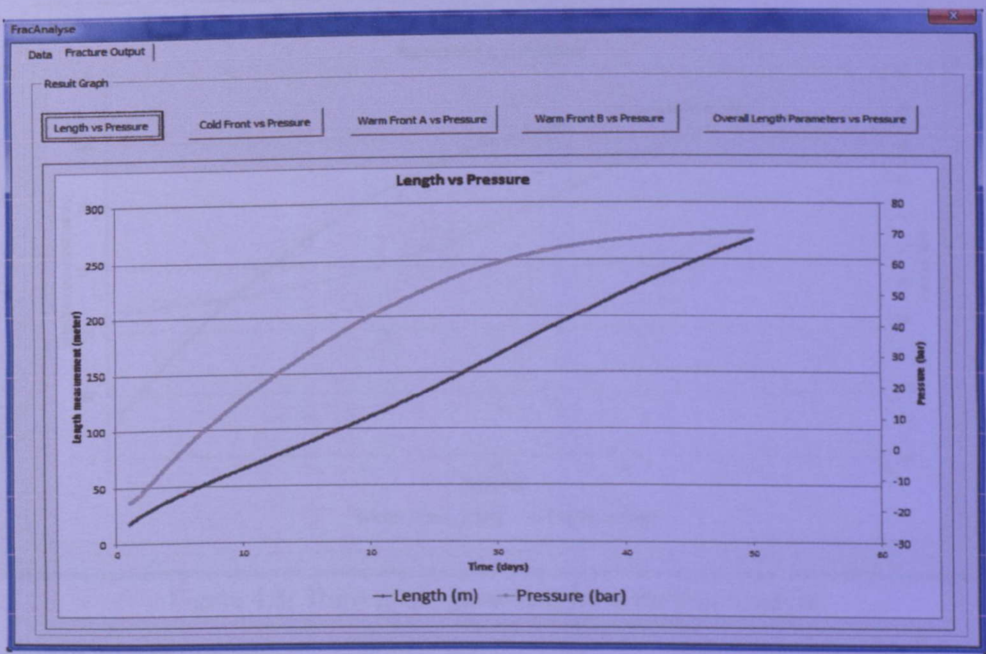

Figure 4.6: First result graph generated from the FracAnalyse

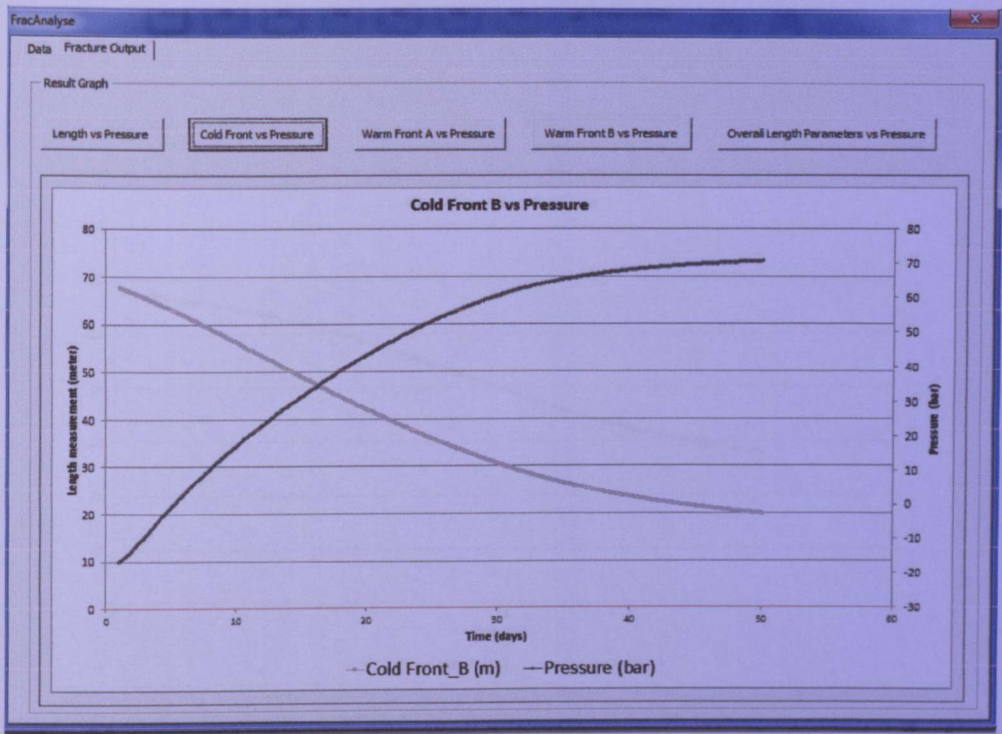

Figure 4.7: Second graph generated from the FracAnalyse

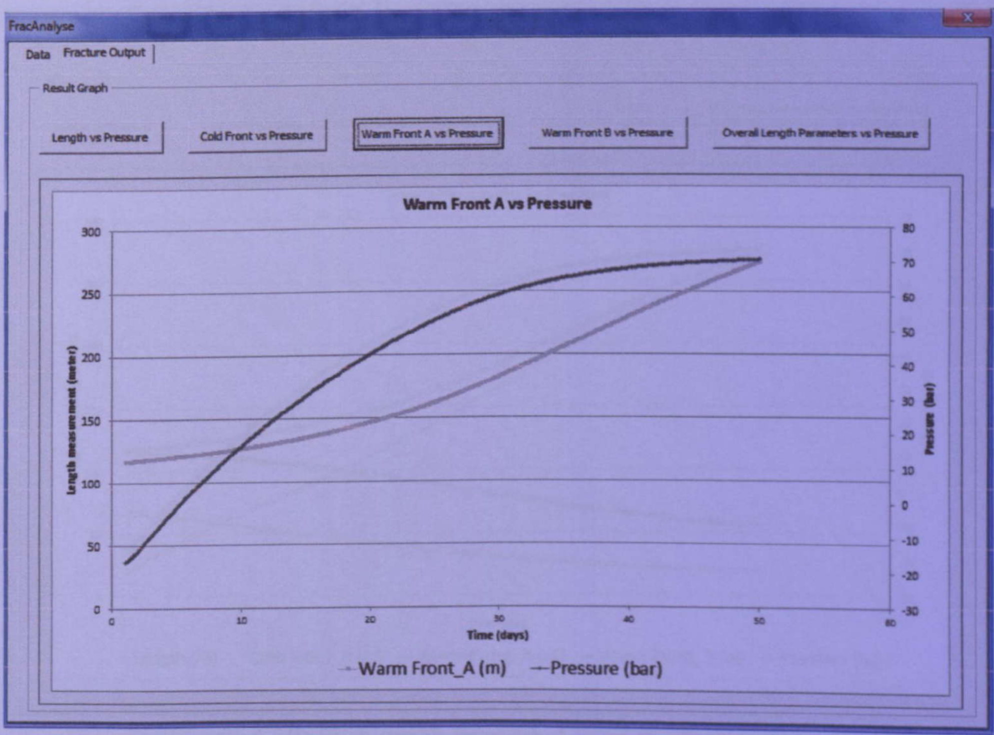

Figure 4.8: Third graph generated from the FracAnalyse

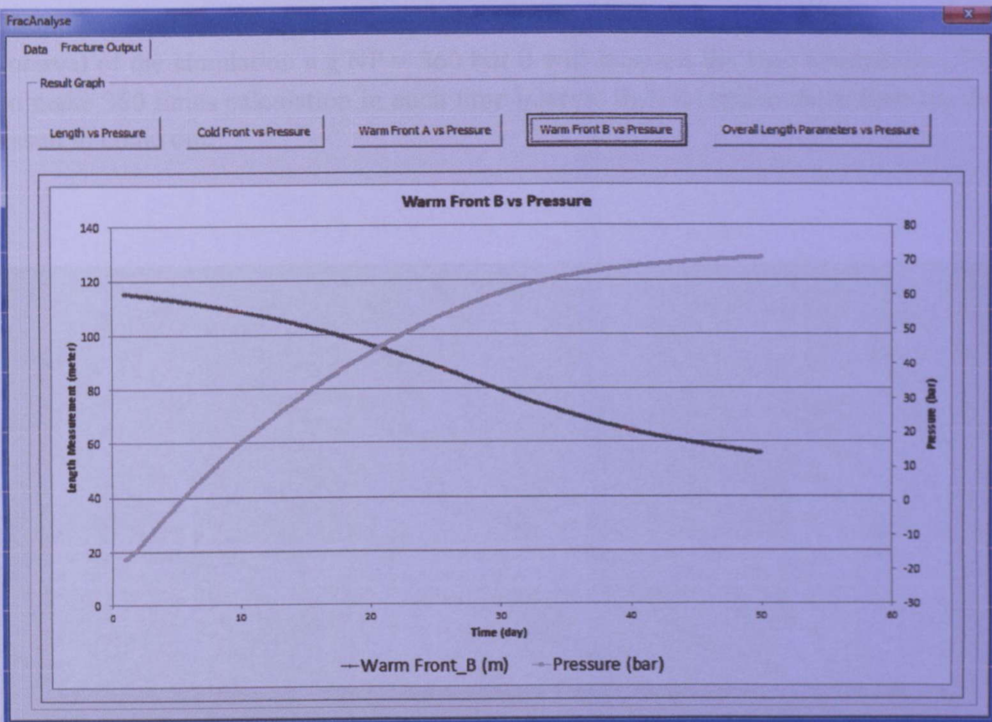

Figure 4.9: Fourth graph generated from the FracAnalyse

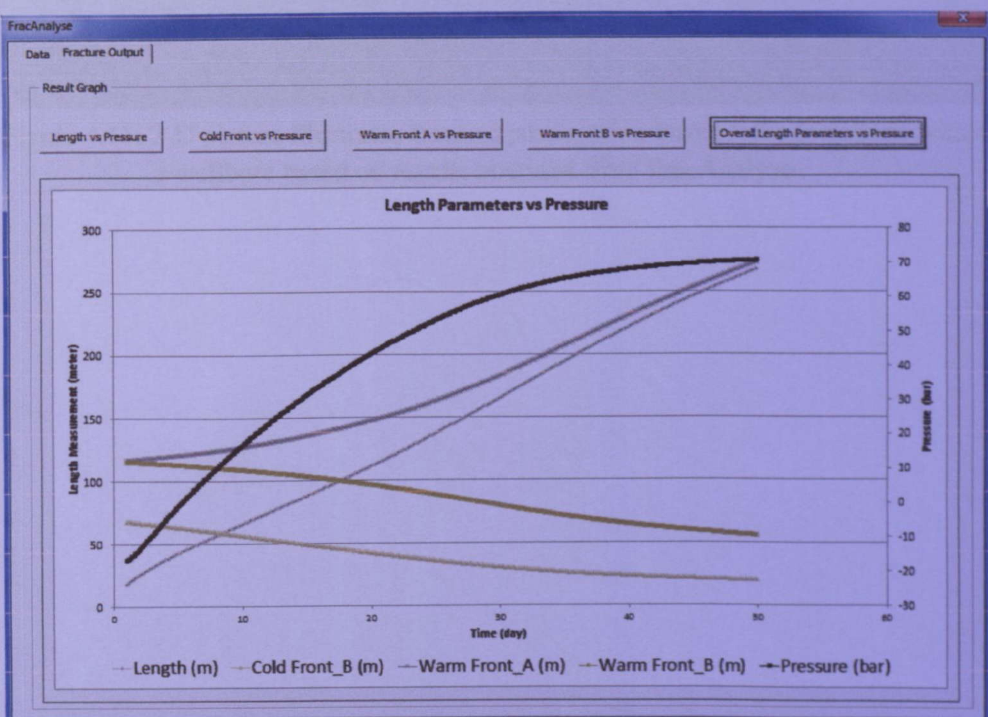

Figure 4.10: Fifth graph generated from the FracAnalyse

The graphs generated in the interface can be customised according to the parameters desired by the users.

Graphical and FracAnalyse results will be more accurate by increasing the time interval of the simulation e.g NP = 360 but it will increase the load toward the CPU to make 360 times calculation in each time interval thus it require more time for the result to come out.

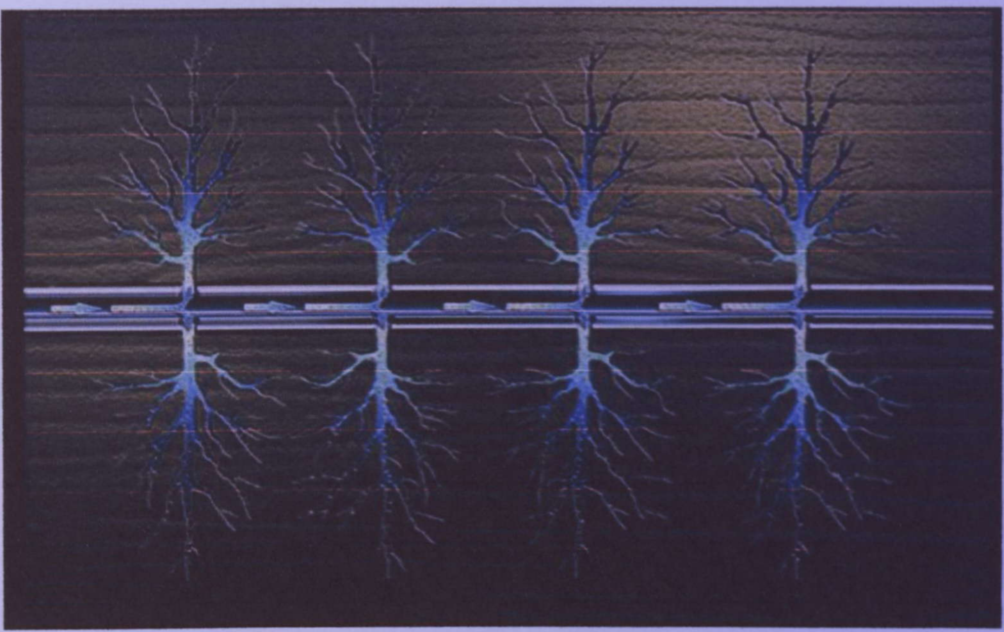

Figure 4.11: 2-D picture illustrates fracture propagation through the formation within a wellbore based on results obtained from FracAnalyse

5.0 Conclusions and Recommendations

Throughout the done research on literature review, methodology, and results obtained through FracAnalyse simulator it is concluded that this project has reached its objectives which are:

i. Investigate the fracture initiation along with its propagation in a cold water injection scenario,

ii. Quantify the stability of fracture and leak-off rate at the fracture surface, and

iii. Develop an in-house software which can stimulate a well simulate reservoir.

It is clearly hydraulic fracturing plays significant role in well stimulation technique to improve recovery. Fracture propagation in a cold water injection can be achieved through certain conditions and circumstances however a more elaborated and detailed well stimulation needed to be done in order to achieve high accuracy of the desired result. In perspective of generated results every parameters included in the module and FracAnalyse are essential in manipulating the fractured length.

Recommendations for future improvements in this project are:

i. Investigate fracture propagation based on the effect of rock thermoelasticity and temperature

ii. Investigate the maximum or minimum value of other parameters such as injection volume and porosity to sustain the fracture stability within the borehole

iii. Simplify the GUI by hiding the workbook showing only the application and reducing the steps to obtain results and graphs

References

1. Advani, S.H., Lee, J.K., Khattab, H.A, Oguzhan,G. (1996). Fluid Flow and Structural Response Modelling Associated with the Mechanics of Hydraulic Fracturing, SPE Formation Evaluation, 1(3), 309-318. doi: 10.2118/10846-PA

2. Aziz, K., Settari, A. (1979). Petroleum Reservoir Simulation. Applied Science Publishers Ltd. London

3. Clark, J. B. (1949). A Hydraulic Process for Increasing the Productivity of Wells. Published in Petroleum Transaction. AIME, 186, 1-2. doi: 949001-G

4. Dikken, B.J, Nikko, H. (1987). Waterflood-Induced Fractures : A Simulation Study of their Propagation and Effects on Waterflood Sweep Efficiency. SPE Conference Paper, 978-1-55563-593-0. doi: 10.2118/16551-MS

5. Economides, M. J., Nolte, K. G. (2000). Reservoir stimulation (3rd ed.), Mechanics of Hydraulic Fracturing (pp. 6-1-6-7) England, West Sussex : John Wiley & Sons Ltd.

6. Geertsma, J., de Klerk, F. (1969). A rapid method for predicting width and extent of hydraulically induced fractures. SPE Reprint Series. Hydraulic Fracture, 1(28), 73-83. doi: 10.2118/2458-PA

7. Ji Lujin, Settari,A. (2004). Method for Modeling Dynamics Fractures in Coupled Reservoir and Geomechanics Simulation, SPE 90874. doi: 10.2118/90874-MS

8. Hagoort, J. (1980). Modeling the Propagation of Waterflood-Induced Hydraulic Fractures. SPE Journal, 4 and 20, 293-300. doi: 10.2118/7412-PA

9. Hubbert, M. K., Willis, D. G. (1957). Mechanics of hydraulics fracturing. Published in Petroleum Transactions. AIME, 210, 153-155. doi: 686-G

10. Nordgren, R.P. (1972). Propagation of a vertical hydraulic fracture. SPE Journal, 12(4), 306-314. doi: 10.2118/3009-PA

11. Perkins, T.K., Gonzalez, J.A. (1985). The Effect of Thermoelastic Stresses on Injection Well Fracturing, SPE Journal, 25(1), 78-88. doi: 10.2118/11332-PA

12. Perkins, T.K, Gonzales, J.A. (1984), Changes in Earth stresses around a wellbore caused by radially symmetrical pressure and temperature gradients. SPE Journal, 24(2), 129-140. doi: 10.2118/10080-PA

13. van Poolen, H. K. (1957). Theory of hydraulic fracturing. ARMA Conference Paper, 115 and 125. doi: 57-0113

14. Settari, A. (1980). Simulation of Hydraulic Fracturing Processes,SPE Journal, 20(6) ,487-500. doi: 10.2118/7693-PA

15. Settari,A.,Cleary,M.P. (1984). Three-Dimensional Simulation of Hydraulic Fracturing, SPE Journal,36(7), 1177-1190. doi: 10.2118/10504-PA